A Nucleon Decay Experiment in a National Underground Laboratory

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Topics

- Why it's interesting.
- Brief history
- Current status
- Ideas for next generation of experiments
- Laboratory issues

First Motivation – Test of Conservation Laws

- In particle physics, reactions among particles obey several conservation laws.

For example:

$$
\begin{array}{ccccc}
\mu & \longrightarrow & e & + & \bar{\nu}_e \\
N_{\mu=1}, N_{e=0} & & N_{\mu=0}, N_{e=1} & & N_{\mu=0}, N_{e=-1}
\end{array}
$$

is forbidden – violates "Lepton Number" Conservation.

$$
\begin{array}{ccccccc}
\mu & \longrightarrow & e & + & \bar{\nu}_e & + & \nu_\mu \\
N_{\mu=1}, N_{e=0} & & N_{\mu=0}, N_{e=1} & & N_{\mu=0}, N_{e=-1} & & N_{\mu=1}, N_{e=0}
\end{array}
$$

- Some – familiar from classical physics – based on general theoretical principles.
- Others – purely empirical – without any obvious theoretical justification. Proposed to account for absence of some reactions.
- In general, we expect any reaction not forbidden by a conservation law will occur – although maybe not very often…

- Energy
- Momentum
- Angular momentum
- Electric Charge
- Baryon Number
- Lepton Number

Predicted by basic laws of mechanics and electromagnetism

No obvious theoretical foundation.

Symmetries

- Conservation laws correspond to mathematical properties (symmetries) which can help us understand the reason for the law.
- Translational => Momentum
- Rotational => Angular Momentum
- Time Translation => Energy
- U(1) gauge => Charge

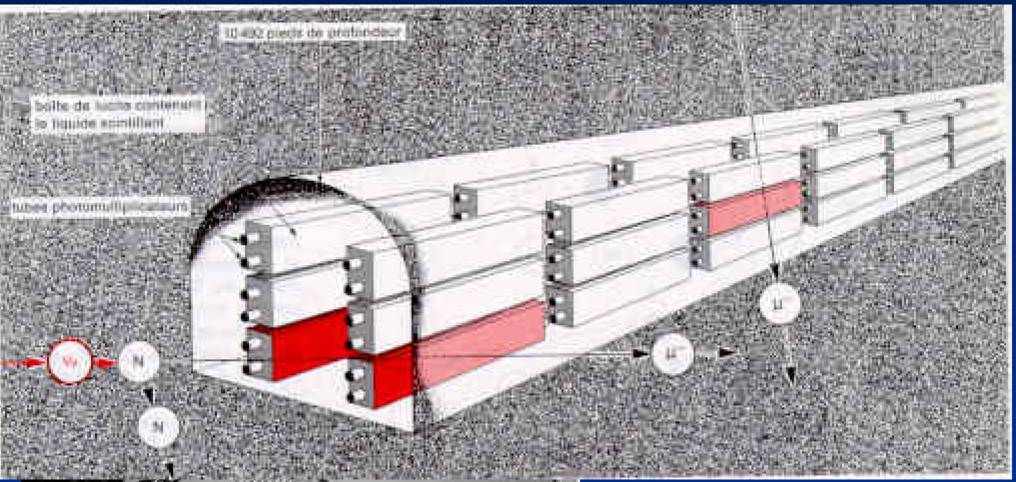
Baryon Number Conservation

- Net number of Baryons remains constant.
  - Baryons are massive particles which are made up of three quarks in the standard model. This class of particles includes the proton (UUD) and neutron (DDU). Some other baryons are the lambda (UDS), sigma, xi, delta and omega (SSS) particles.
- If the proton decayed this law would have to be violated.
  - For energy reasons it can’t decay to a different baryon.

Brief History

1954 Goldhaber	Spontaneous fission of U^{232}	1.4×10^{18} years
1954 Reines, Cowan, Goldhaber	Liquid scintillator – 30m below surface	1.0×10^{22} years
1957 Reines, Cowan, Kruse	Deuterated scintillator – 61m below surface	4.0×10^{23} years
1960 Backenstoss, et. al.	Cherenkov and scintillation – 800m below surface	2.8×10^{26} years
1962 Giomati and Reines	Liquid scintillator – 585m below surface	1.0×10^{26} years to 7.0×10^{27} years
1964 Kropp and Reines	Liquid scintillator – 585m below surface	6.0×10^{27} years to 4.0×10^{28} years
1967 -1974 CWI	Liquid scintillator – 3200m below surface	2.0×10^{28} years to 8.0×10^{29} years

CWI – South Africa

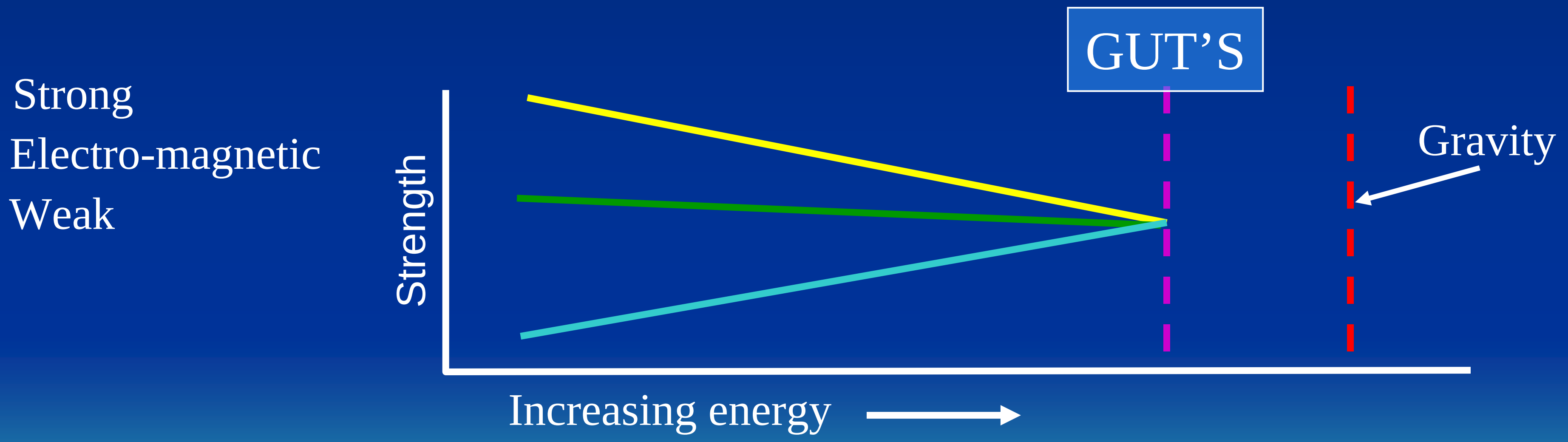


Depth of 11,500 ft
in ERPM gold mine

1965 - 1974

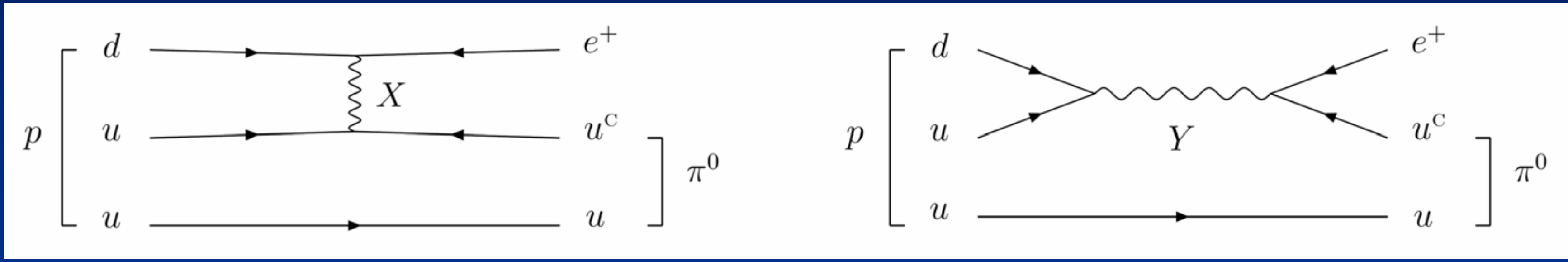
More Recent Motivation – Grand Unification

General idea:
All forces are manifestations of a single force perhaps with only one strength.



First Promising GUT – SU(5)

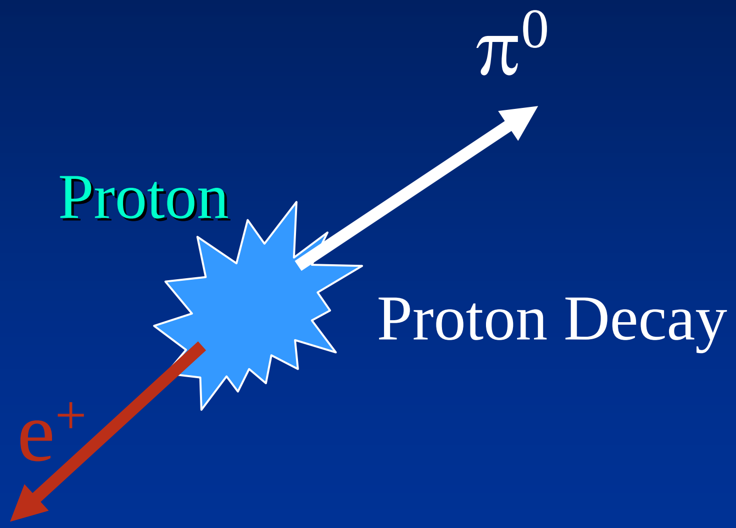
Georgi & Glashow - 1974



- Two quarks in a proton could transform into a lepton and a meson via the exchange of a very heavy gauge boson.
- Since the boson is very heavy it is beyond the reach of accelerator methods.

Proton Decay

- Early SU(5) predicted:
  - lifetime ~ 10^{29} yr
  - 40-60% $p \longrightarrow e^{+} + \pi^{0}$
- Requires comparable number of protons
  - (~6×10^{29} nucleons/ton)



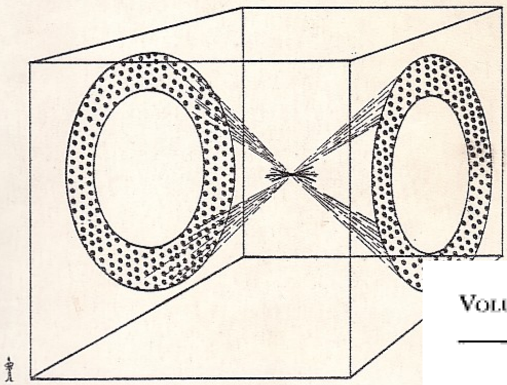
IMB

May, 1979

PROPOSAL FOR A

NUCLEON DECAY DETECTOR

IRVINE/MICHIGAN/BROOKHAVEN



- 8kton detector
- 1570 mwe
- ~2x10^{33} nuc/fv

1983: $\tau/\beta > 1.9 \times 10^{31}$ yr

VOLUME 51, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

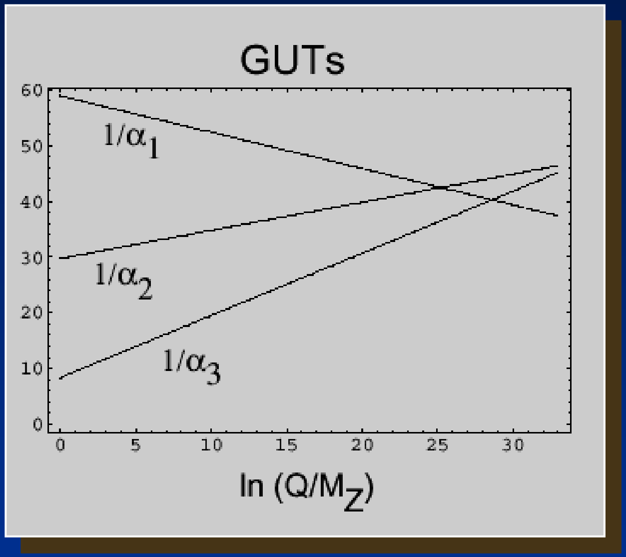
Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p \to e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5 \times 10^{31}$ yr; for free protons the limit is $\tau/B > 1.9 \times 10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

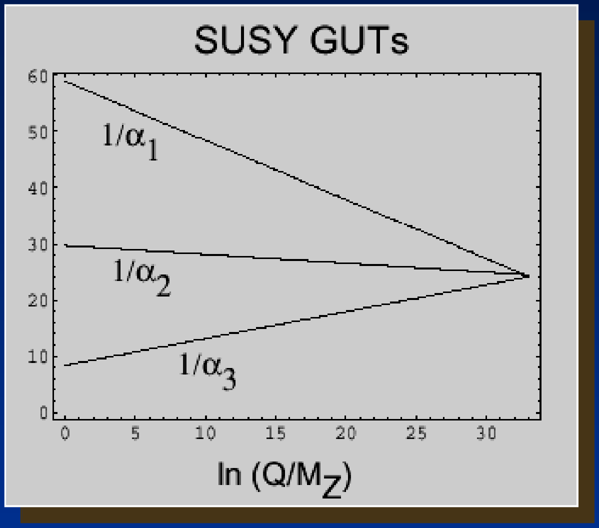
PACS numbers: 13.30.Eg, 11.30.Ly, 14.20.Dh

Extensions to SU(5) and Supersymmetry

- Since the time of IMB, a wide variety of alternative GUTs have been developed including:
  - assumption that fundamental symmetry is bigger than SU(5).
  - possibility of supersymmetry.
    - Symmetry that gives every particle that transmits a force (a boson) a partner particle that makes up matter (a fermion), and vice versa.

=> New modes of decay and longer lifetimes.





Minimal SU(5)

Predicts $p \rightarrow e^+ \pi^0$ 40-60%

Ruled out by IMB + LEP

Supersymmetric GUTs

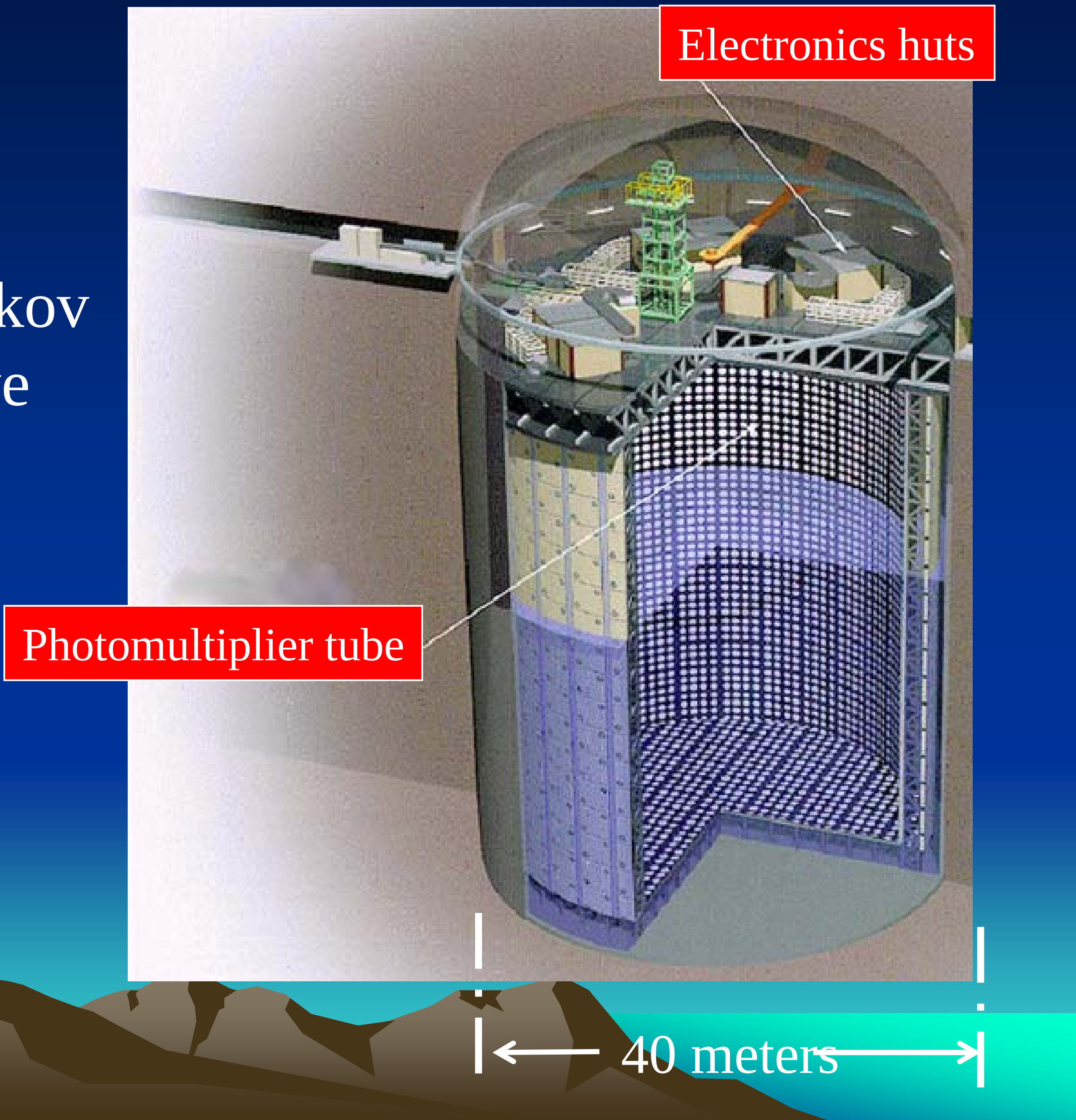
Seem to lead to unification at a single point.

Favors $p \rightarrow \nu K^+$, but also $p \rightarrow e^+ \pi^0$

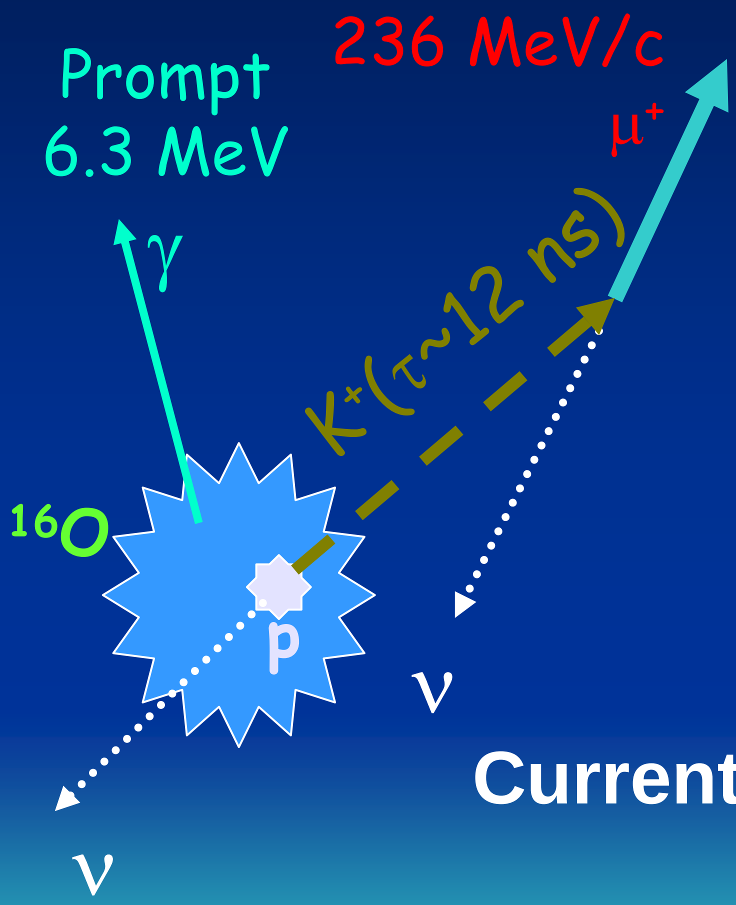
Recent work stresses connection between neutrino masses, mixing and proton decay

Super-Kamiokande

50 kton water Cherenkov detector @2700 mwe



$^{16}O \rightarrow {}^{15}N^{*} + \nu K^{+}$

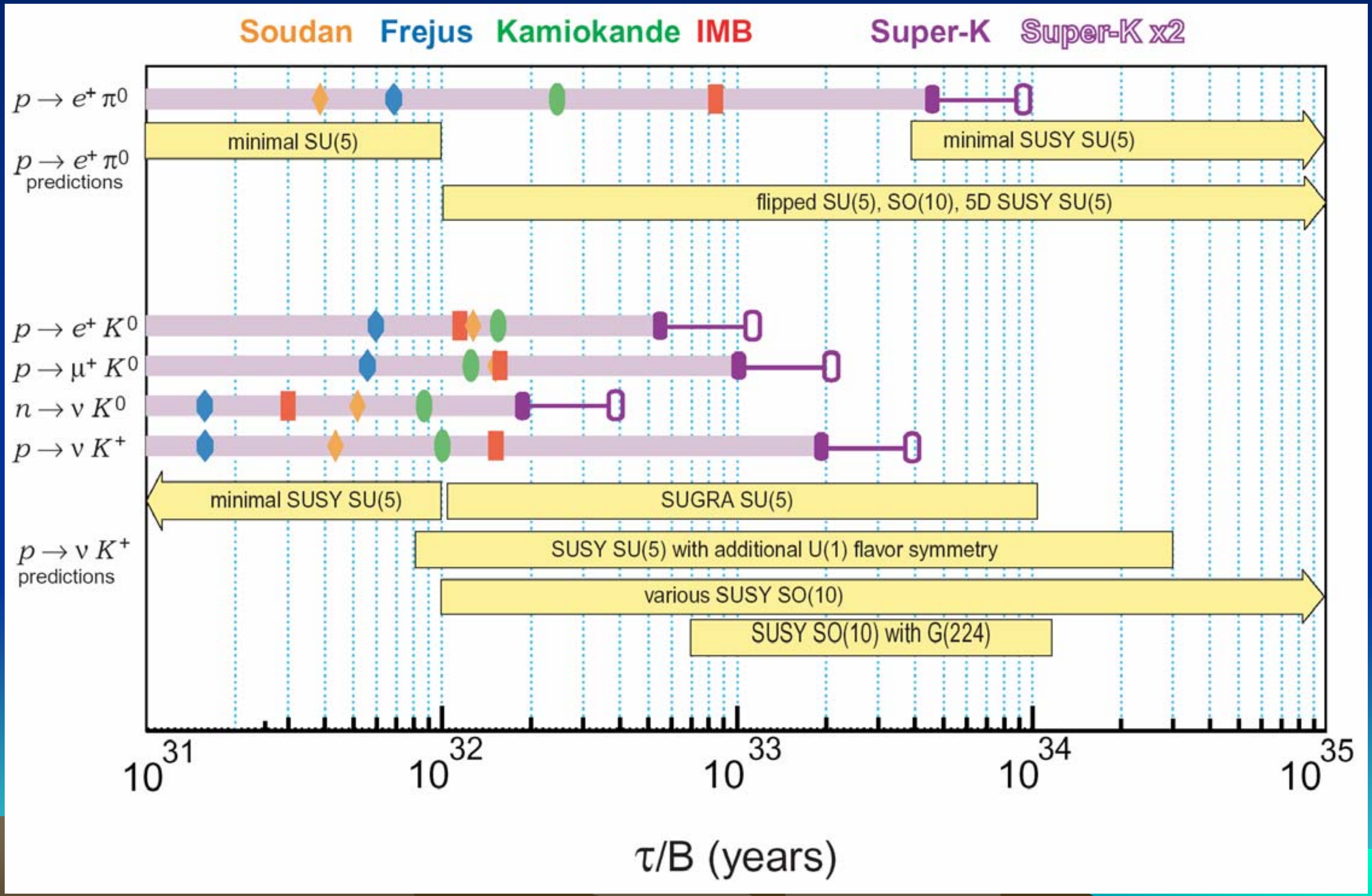


- K^+ below threshold
- K^+ $\mu^+\nu_\mu$ 63.5%
- K^+ $\pi^+\pi^0$ 21.2% $\beta\pi$=0.86
- π+ $\mu^+\nu_\mu$ muon below Cherenkov threshold

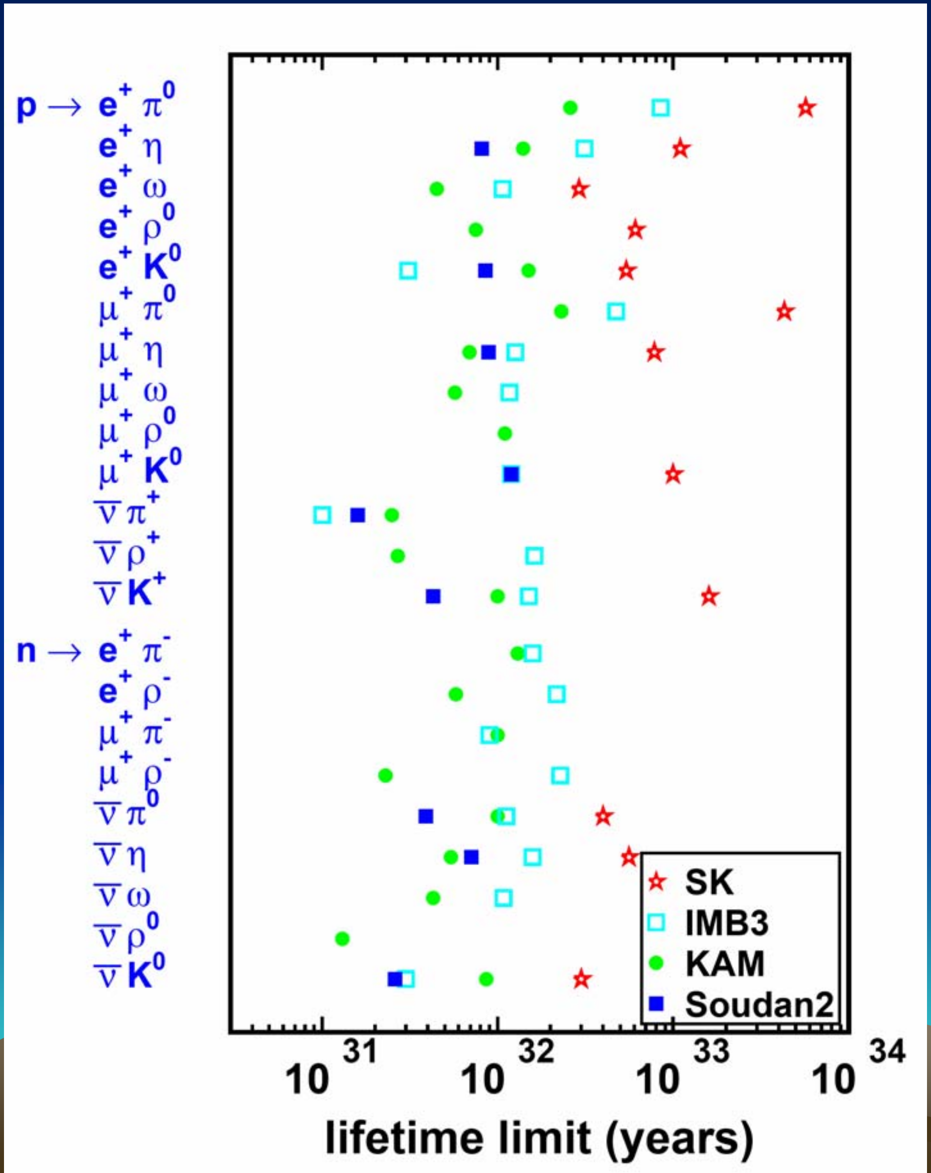
Current limit τ/β p $\rightarrow \nu K^+ > 2.3\text{x}10^{33}$ yrs

Latest Results

1979 – present -- Post-GUTs experiments



Other Modes

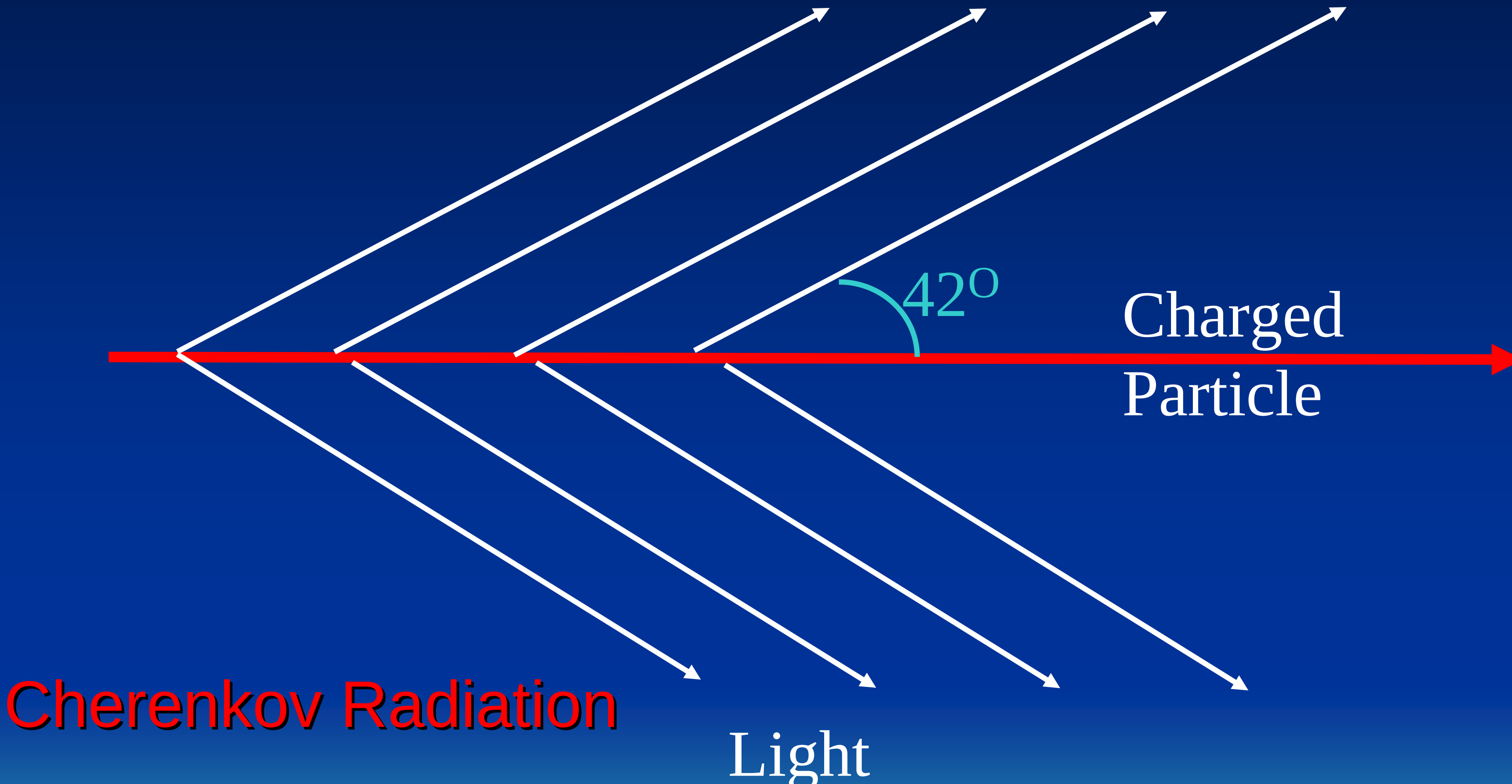


p → e⁺ π⁰
e⁺ η
e⁺ ω
e⁺ ρ⁰
e⁺ K⁰
μ⁺ π⁰
μ⁺ η
μ⁺ ω
μ⁺ ρ⁰
μ⁺ K⁰
ν̄ π⁺
ν̄ ρ⁺
ν̄ K⁺
n → e⁺ π⁻
e⁺ ρ⁻
μ⁺ π⁻
μ⁺ ρ⁻
ν̄ π⁰
ν̄ η
ν̄ ω
ν̄ ρ⁰
ν̄ K⁰
SK
IMB3
KAM
Soudan2
10^31
10^32
10^33
10^34
lifetime limit (years)

Next Generation

- Although positive signature for proton decay remains elusive, the experimental limits are in theoretically interesting territory…
- Sensitivity 10-20 times SK is generally considered for next step.
- There are several experimental techniques that are currently being pursued.

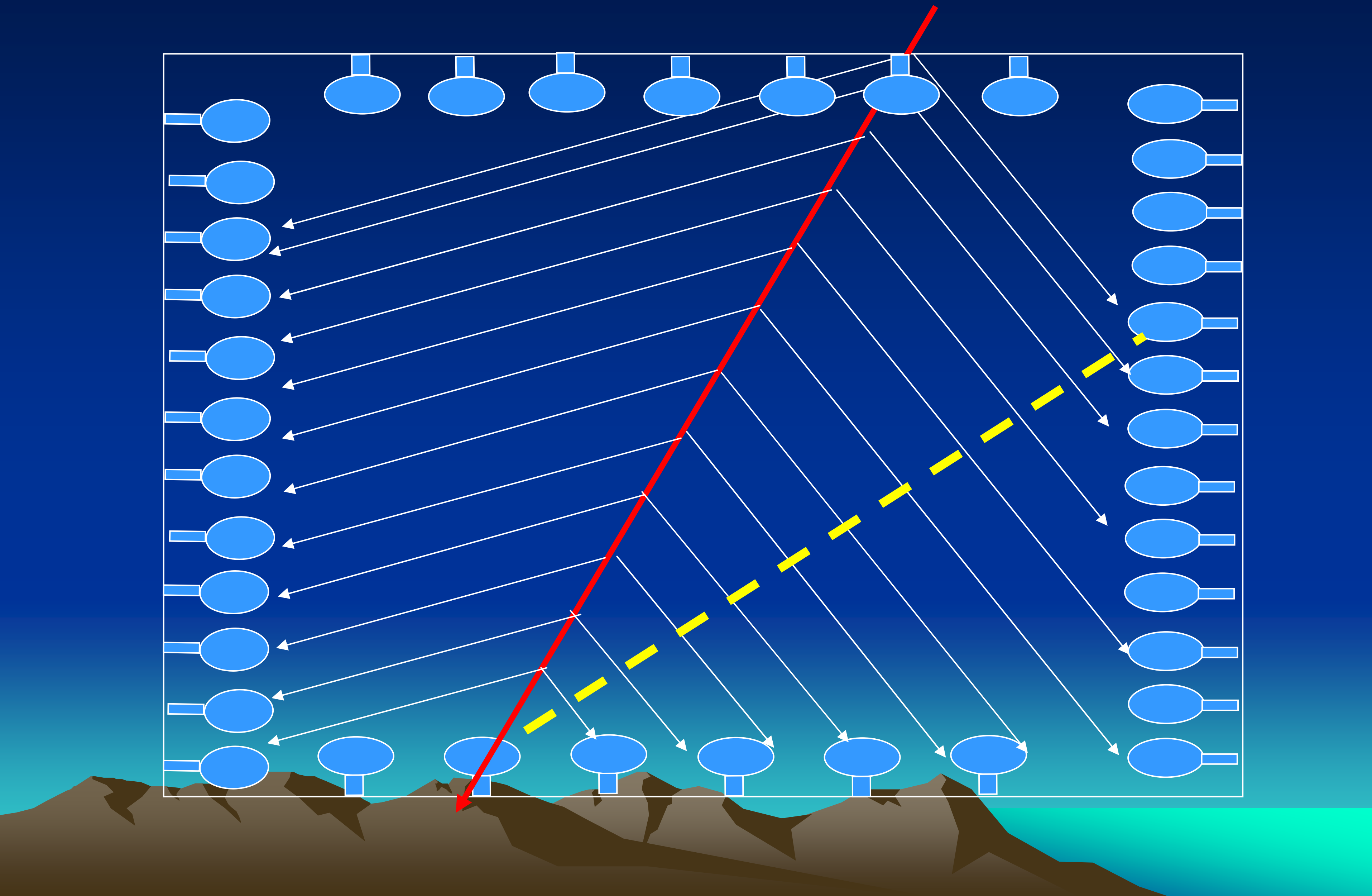
Water Cherenkov



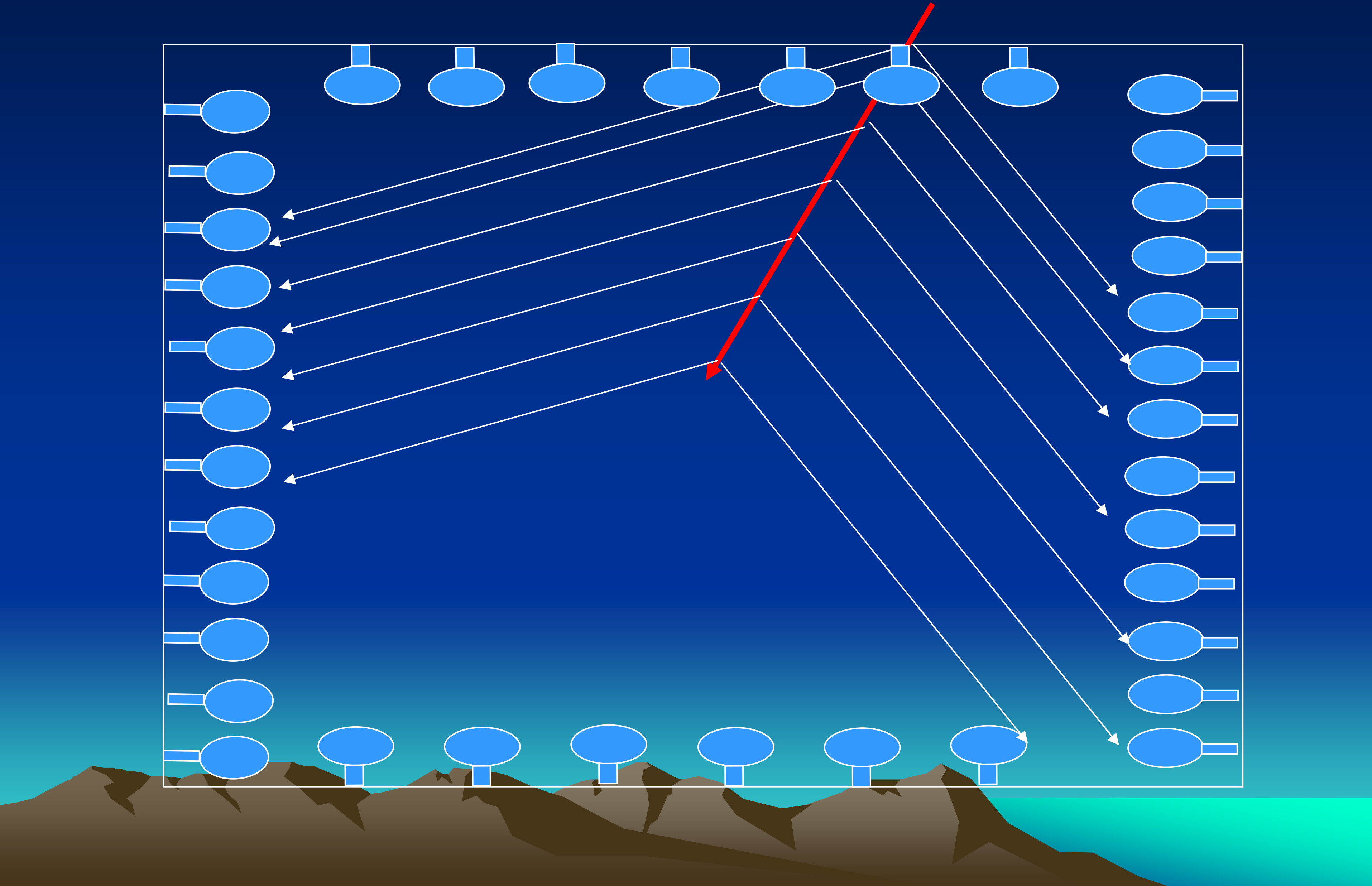
Fixed angle of light to track

About 42 degrees for particle in water

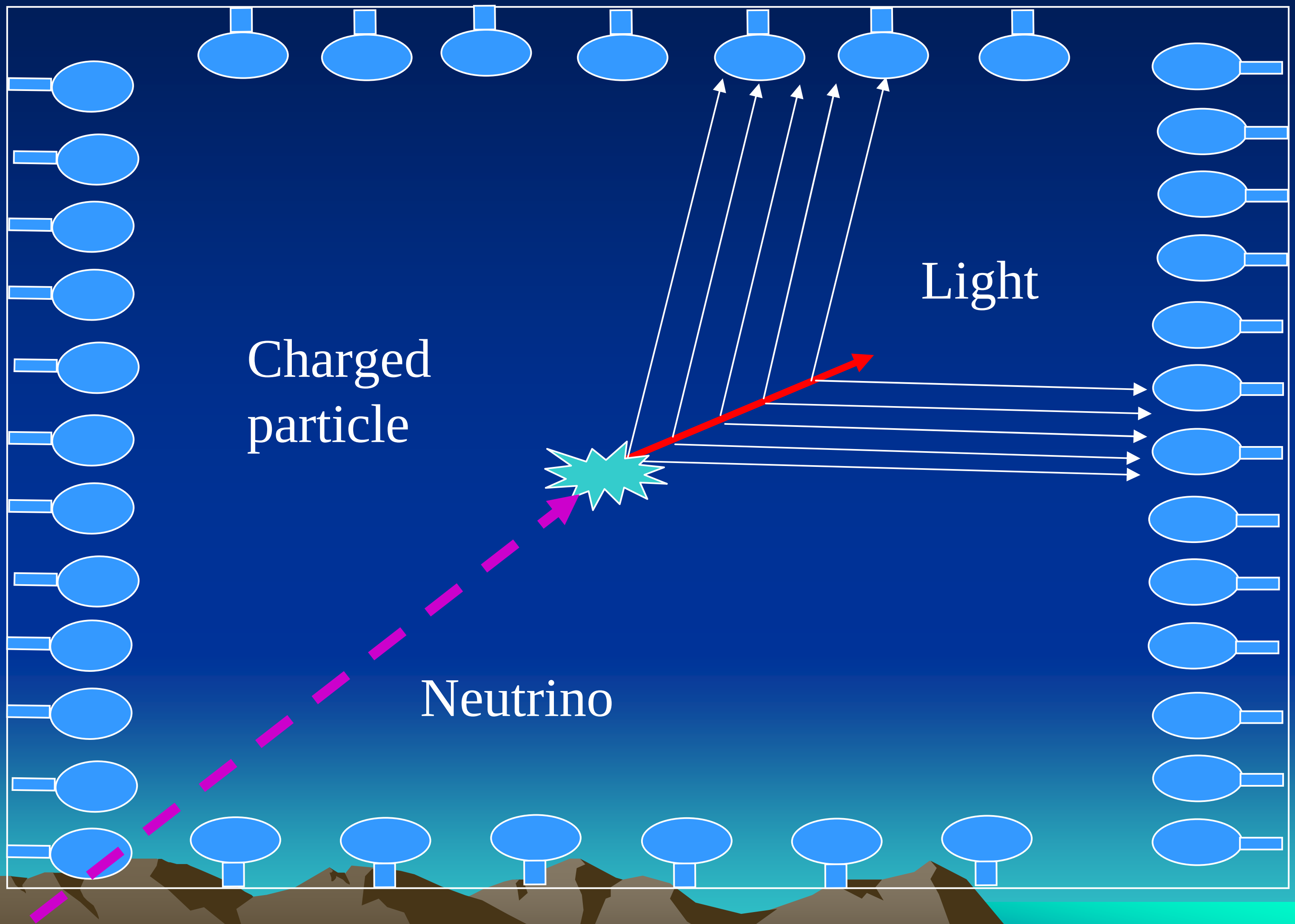
Long Track



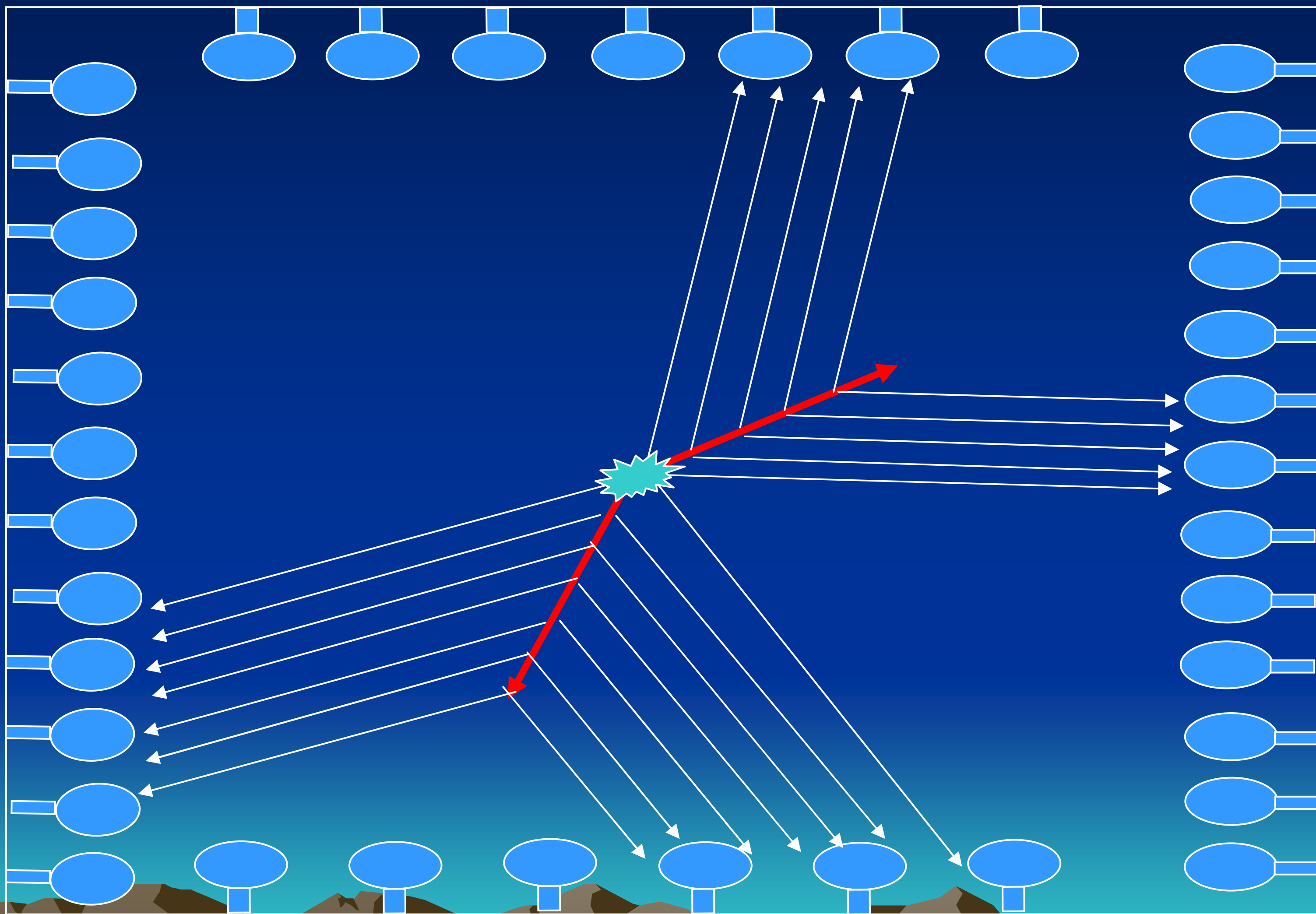
Stopping Track



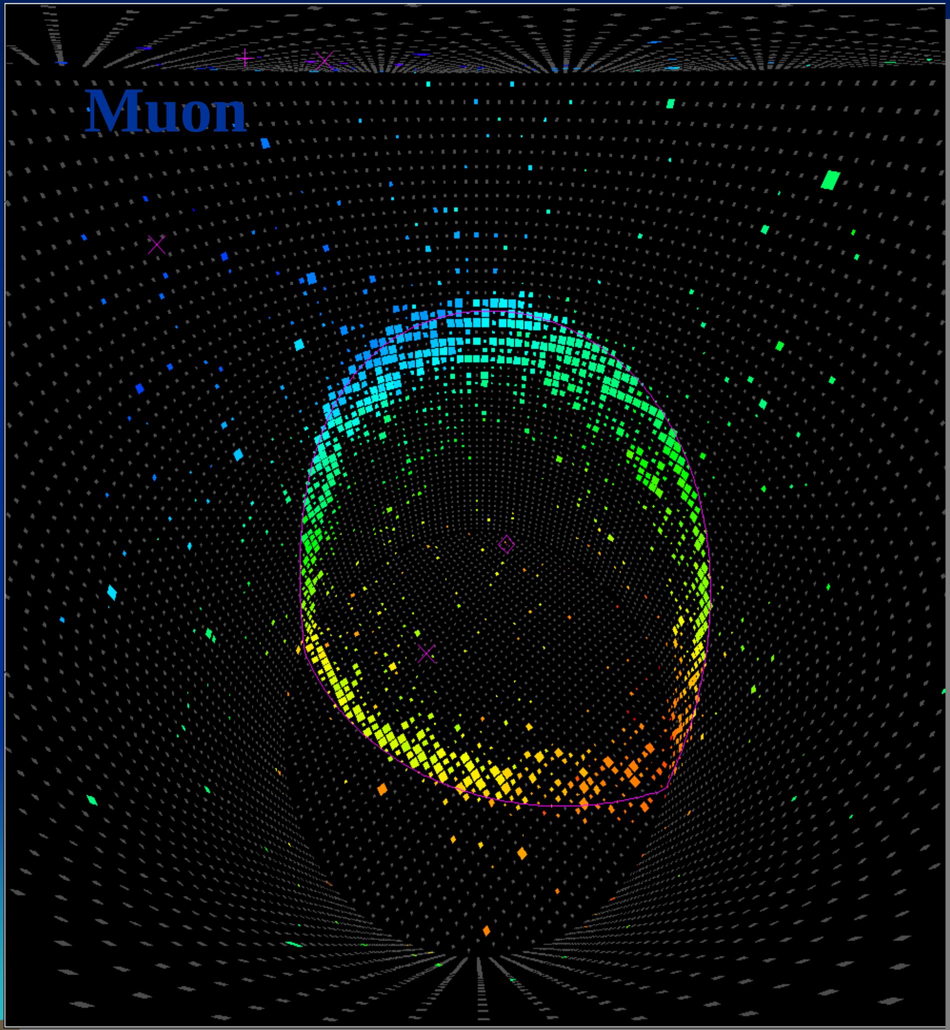
Neutrino

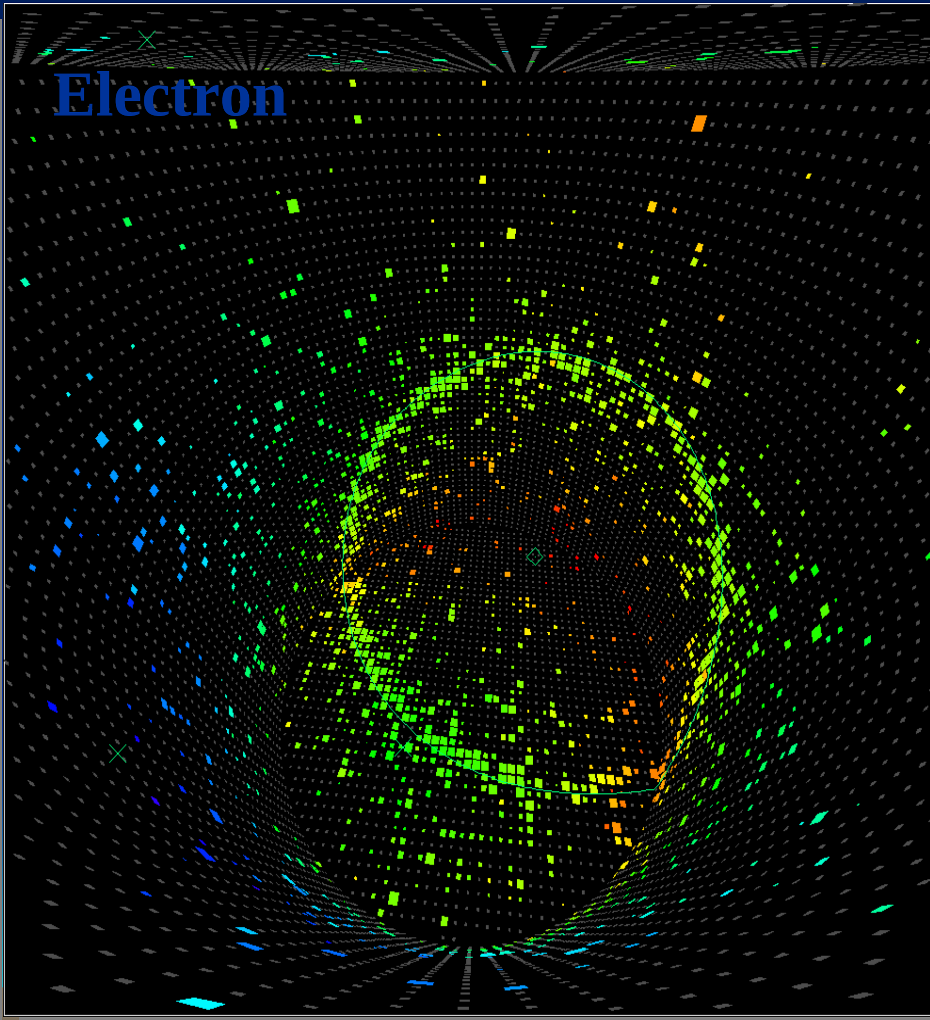


Proton Decay



Particle Identification

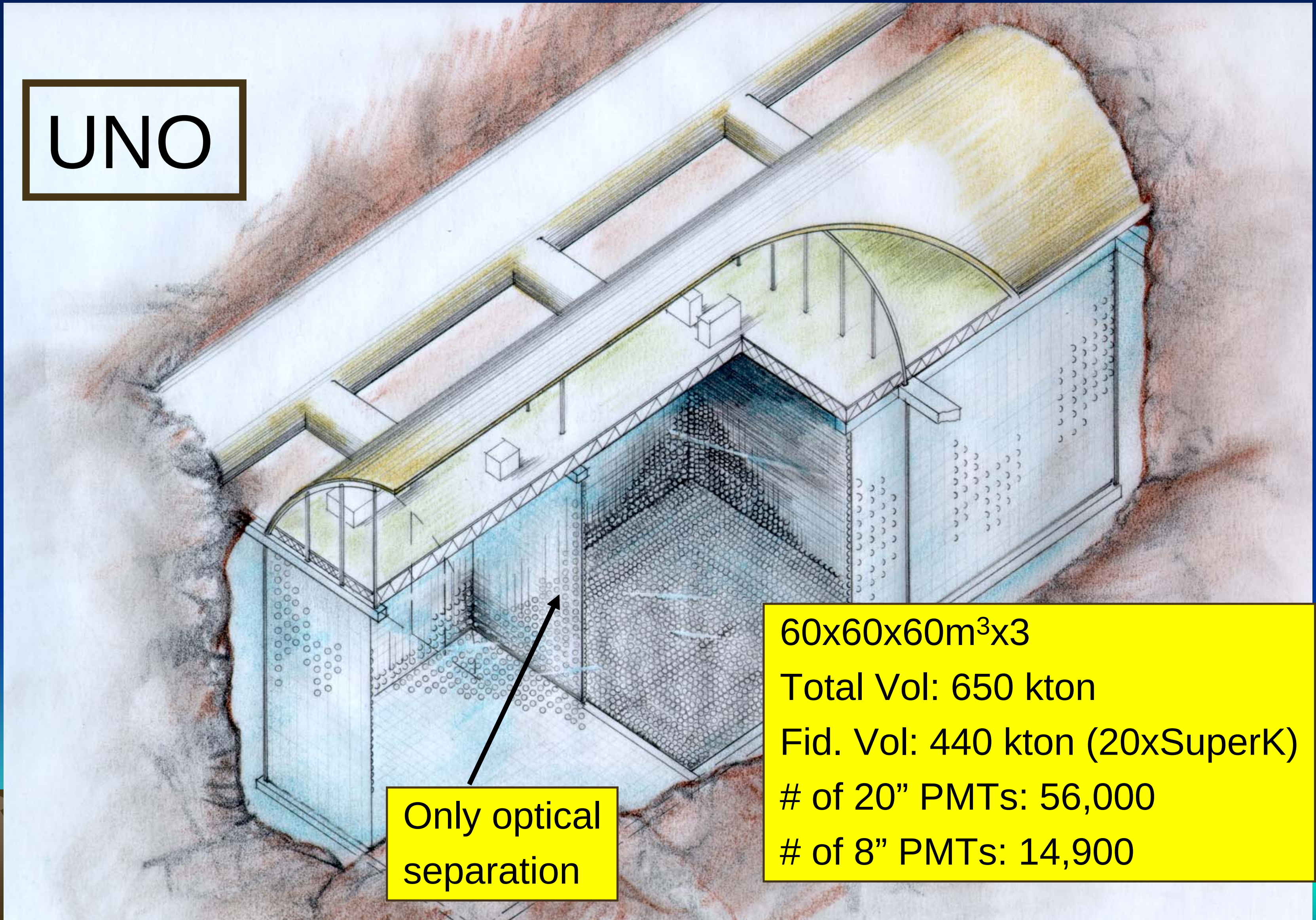




Water Cherenkov

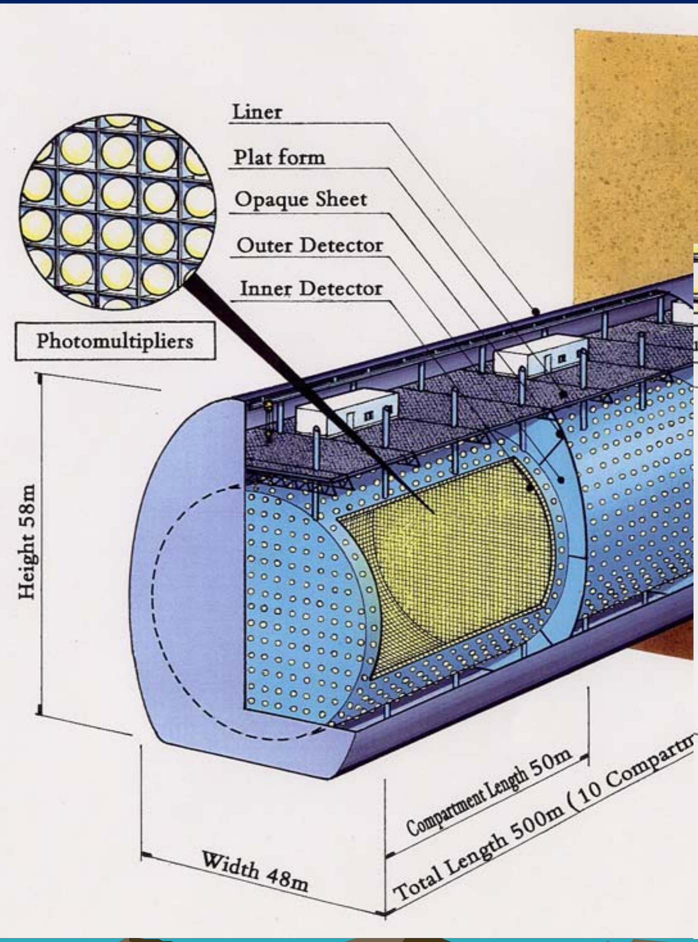
- Cheap target material
- Surface instrumentation
- Vertex from timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and muon decay

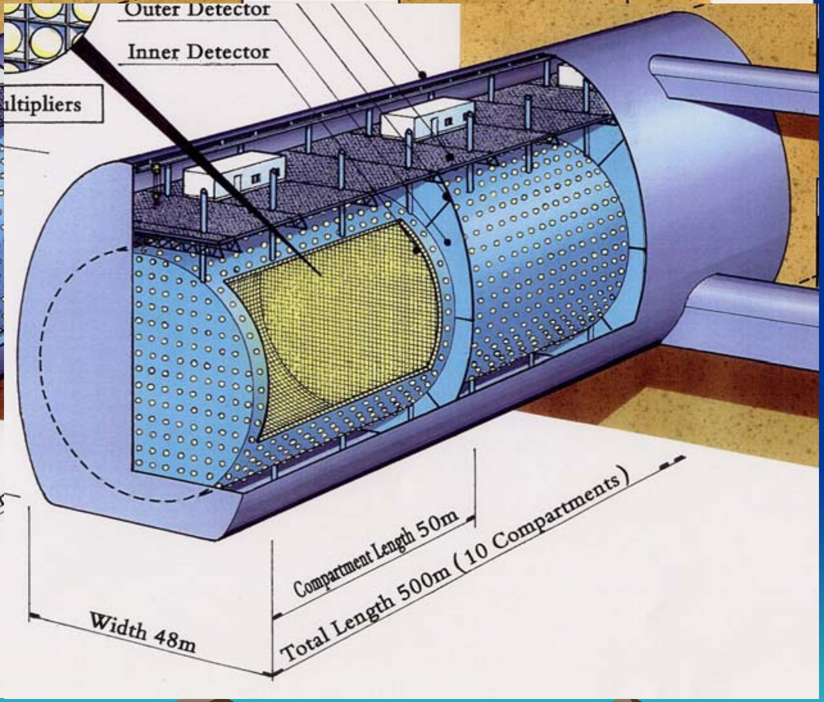
Water Cherenkov Proposals



60x60x60m^{3}x3
Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuperK)
# of 20” PMTs: 56,000
# of 8” PMTs: 14,900

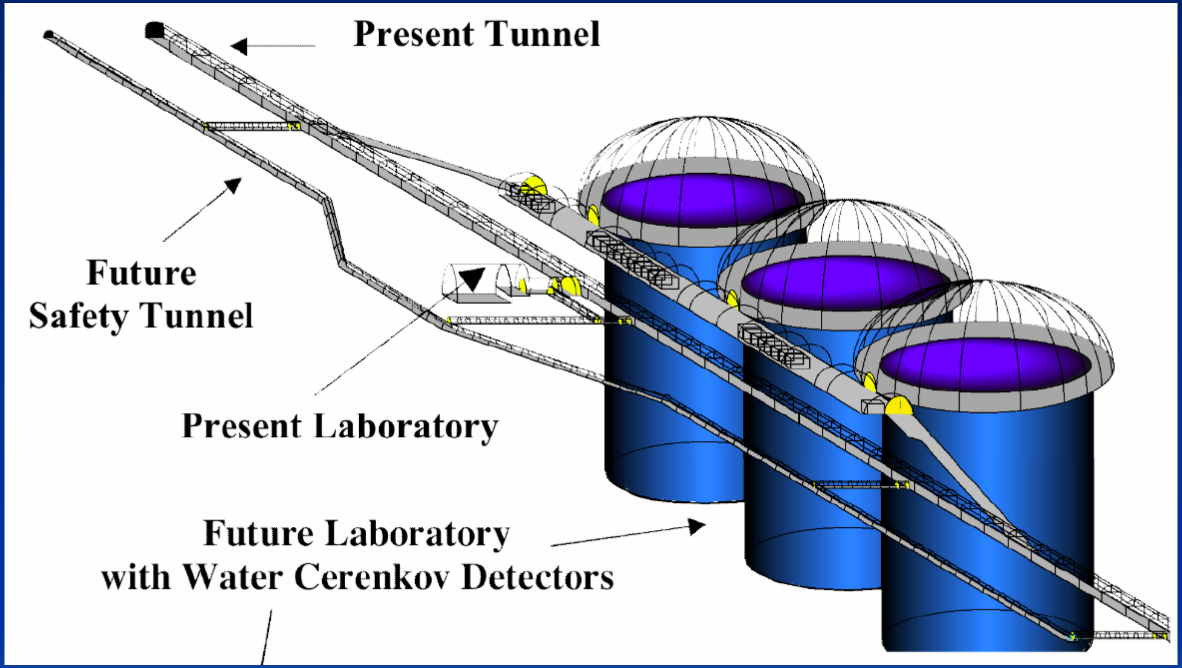
Twin Detector
Hyper-Kamiokande





2 detectors×48m × 50m ×250m, Total mass = 1 Mton

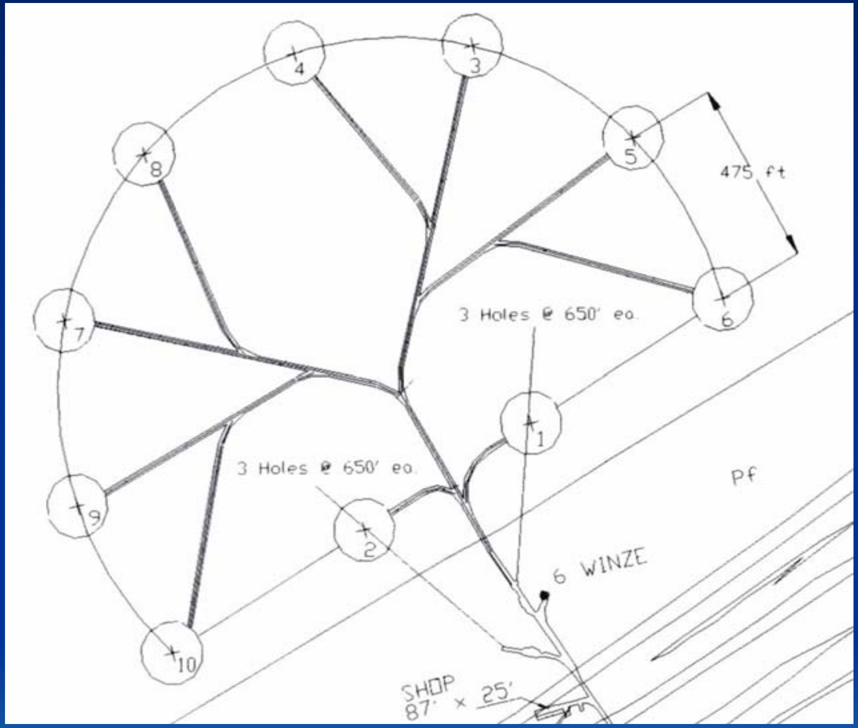
Giant Water Cherenkov at Frejus

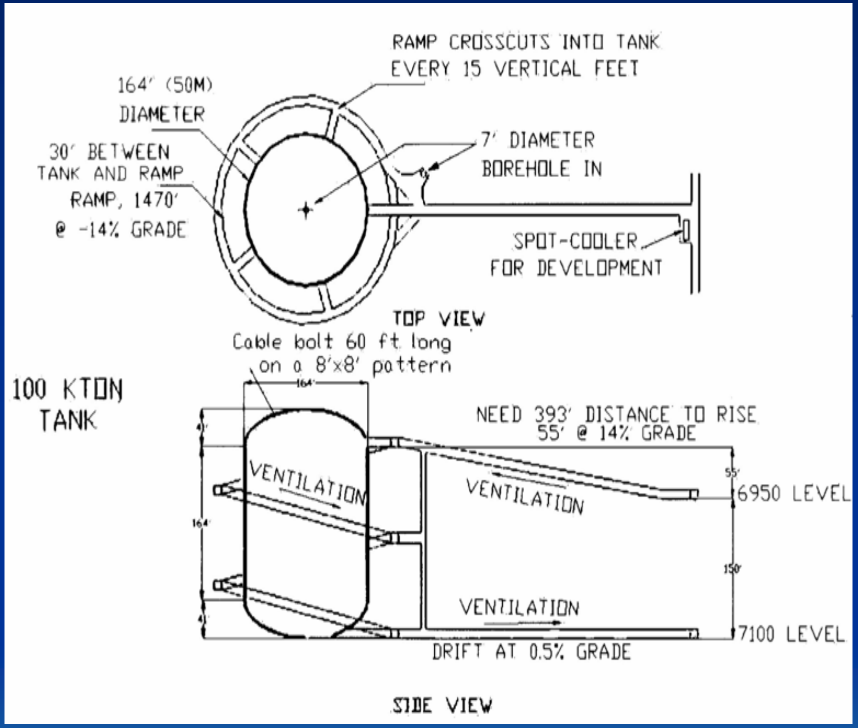


Cavern starting in 2008?

In conjunction with discussion of physics with a Mwatt proton source at CERN…

Megaton Modular Multi-purpose Detector





Limitations of Water Cherenkov Technique

- Insensitive to particles below Cherenkov threshold.
  - Kaon T=253 MeV, Muon T=54 MeV, Pion T=72 MeV,
  - Proton T=481 MeV, Electron T=0.262 MeV
- Low light levels require many PMT's.
- Relatively poor energy resolution.
- Excellent solubility makes it hard to clean.

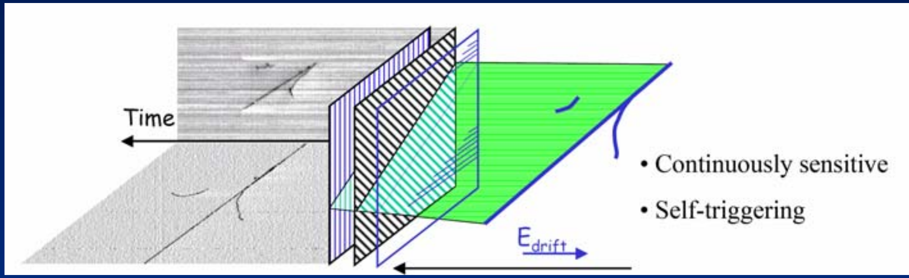
Some Consequences of These Limitations

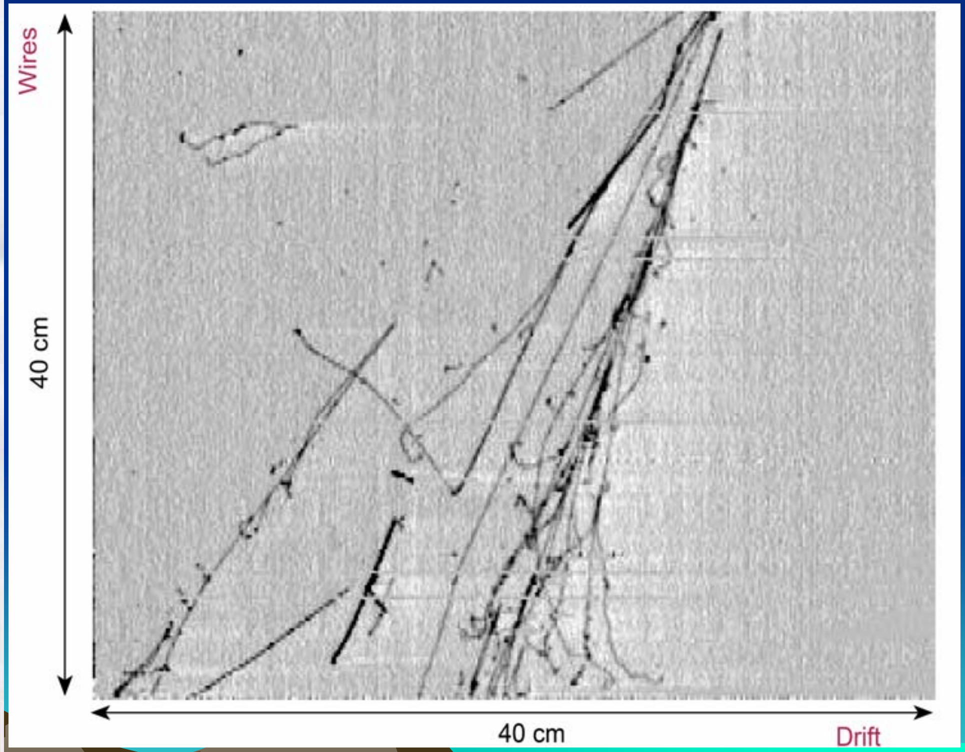
- No K^+ from 2-body nucleon decay can be seen directly.
  - SUSY mode: $P \rightarrow \nu K^+$ very low efficiency
- Many nuclear de-excitation modes not visible directly.
- “Stealth” muons from atmospheric. neutrinos serious background for proton decay, relic SN search.
- Inability to tag radon and other low-level backgrounds.

Liquid Scintillator

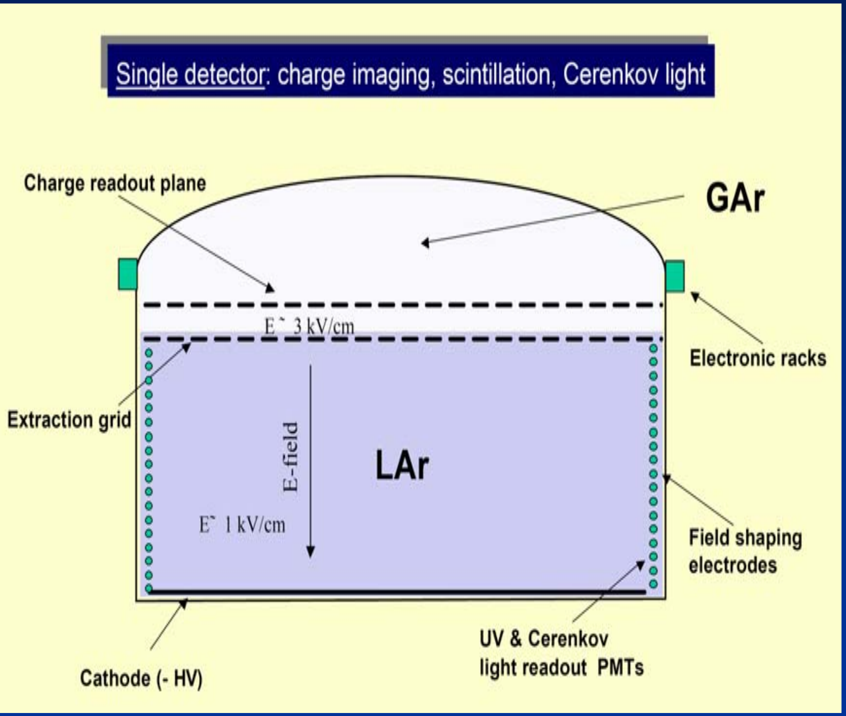
- K^+ are "visible" in scintillator.
- Signal is 3-fold coincidence of K/μ/e, where first two are mono-energetic.
- Potential improvement in efficiency of a factor of 5 to 10 possible using scintillator.
- A test of these ideas is underway using the KamLAND detector.

Liquid Argon Detector



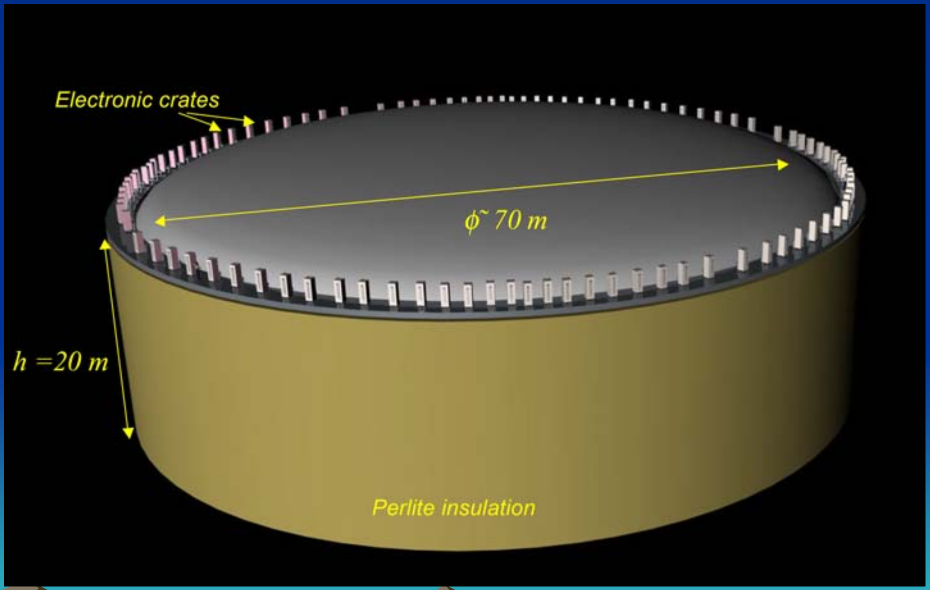


Alternative Configuration

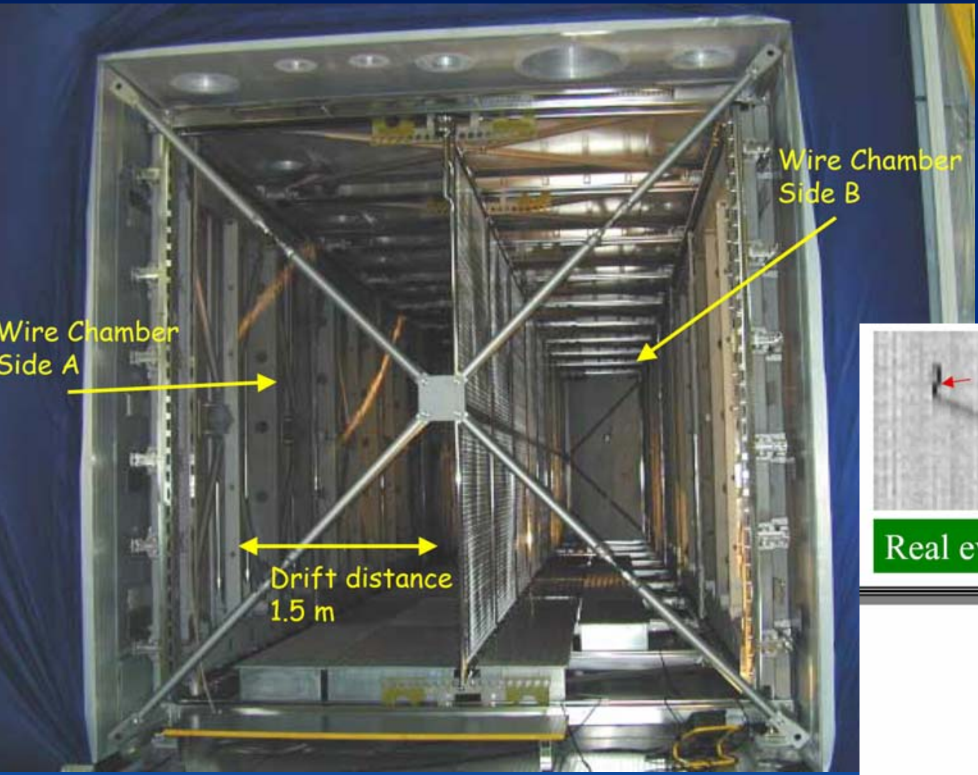


Single volume version with 20m drift

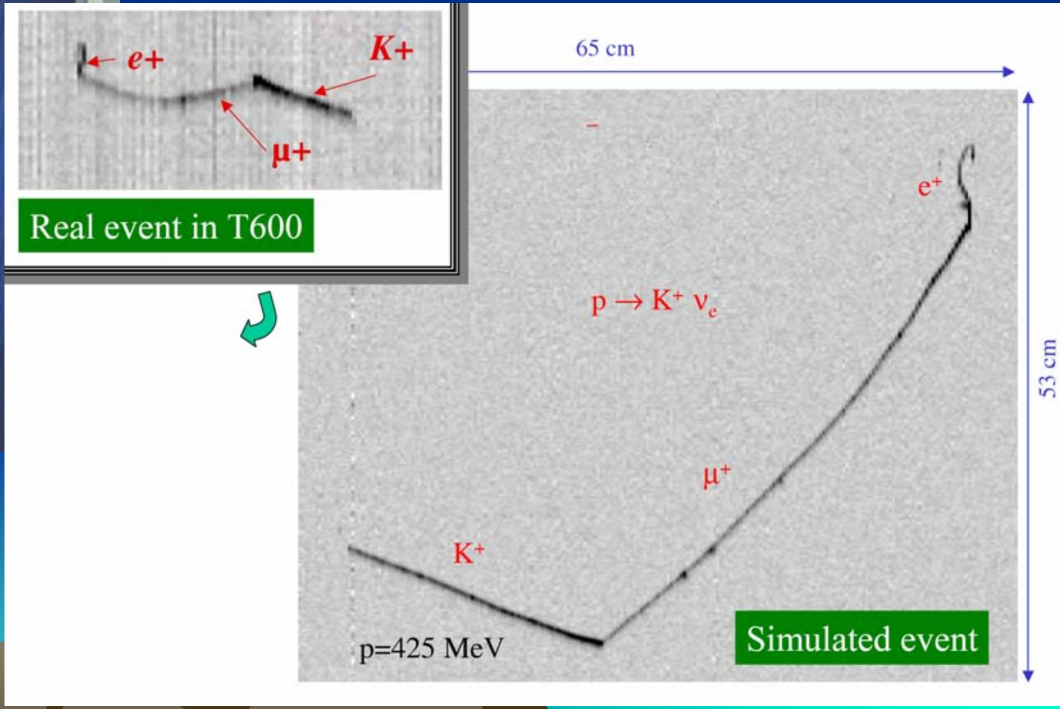
1 kV/cm * 20m = 2×10^6 V



600T Module



K$^+$ REALLY visible in Liquid Argon
$\Rightarrow$K$^+$ modes efficiency ~ 10 times that of water Cherenkov.



Installation and operation at LNGS 2004-2005

Lab Requirements

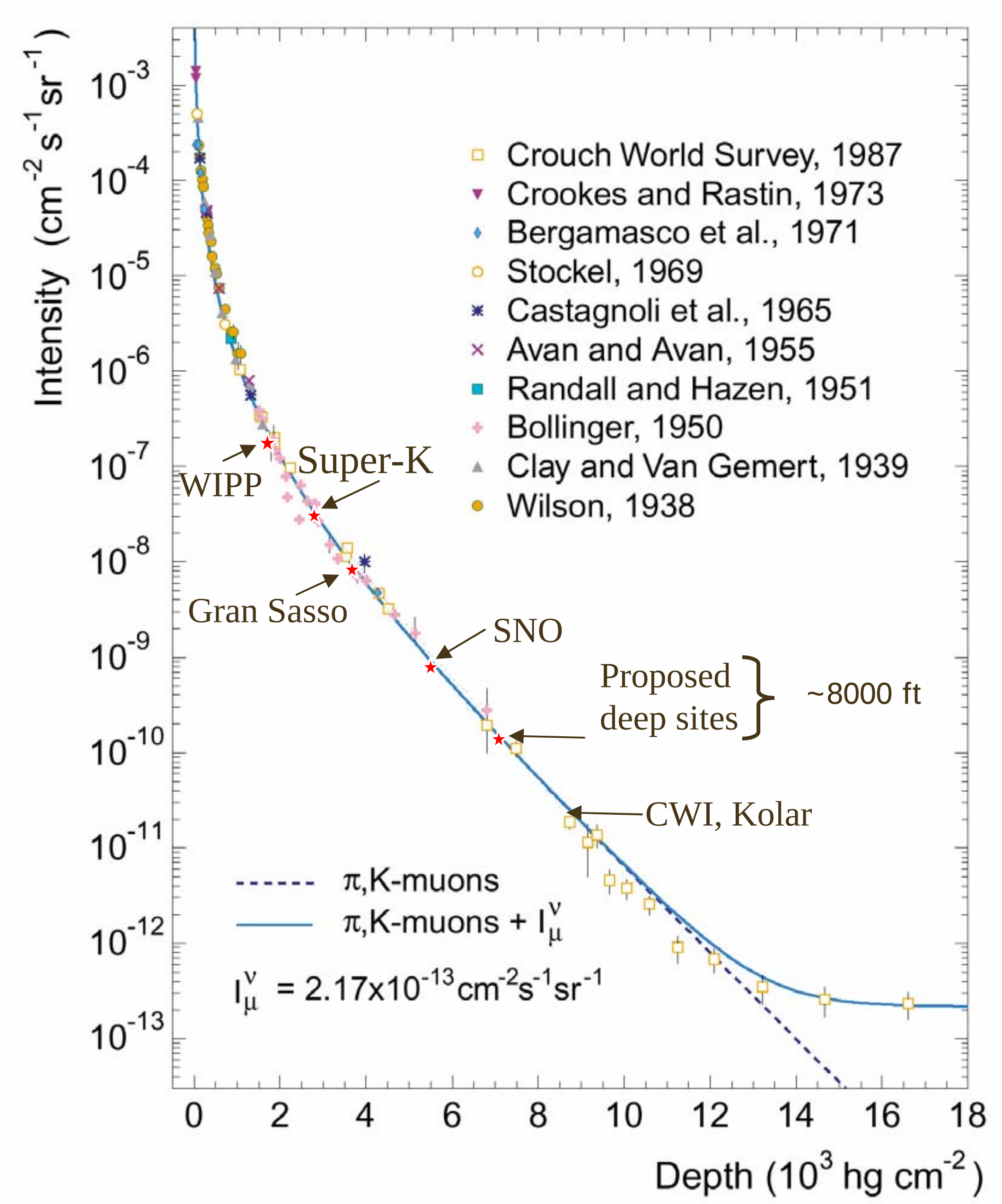
Since we don't know which experimental technology/technologies will ultimately be chosen:

- Ability to excavate large caverns at depth with stable configuration.
- Ability to safely handle large amounts of liquid scintillator.
- Ability to safely deal with possible vaporization of large quantity of liquefied gas.
- Control of Radon gas.
- Large quantities of water available.

Multi-purpose Nature

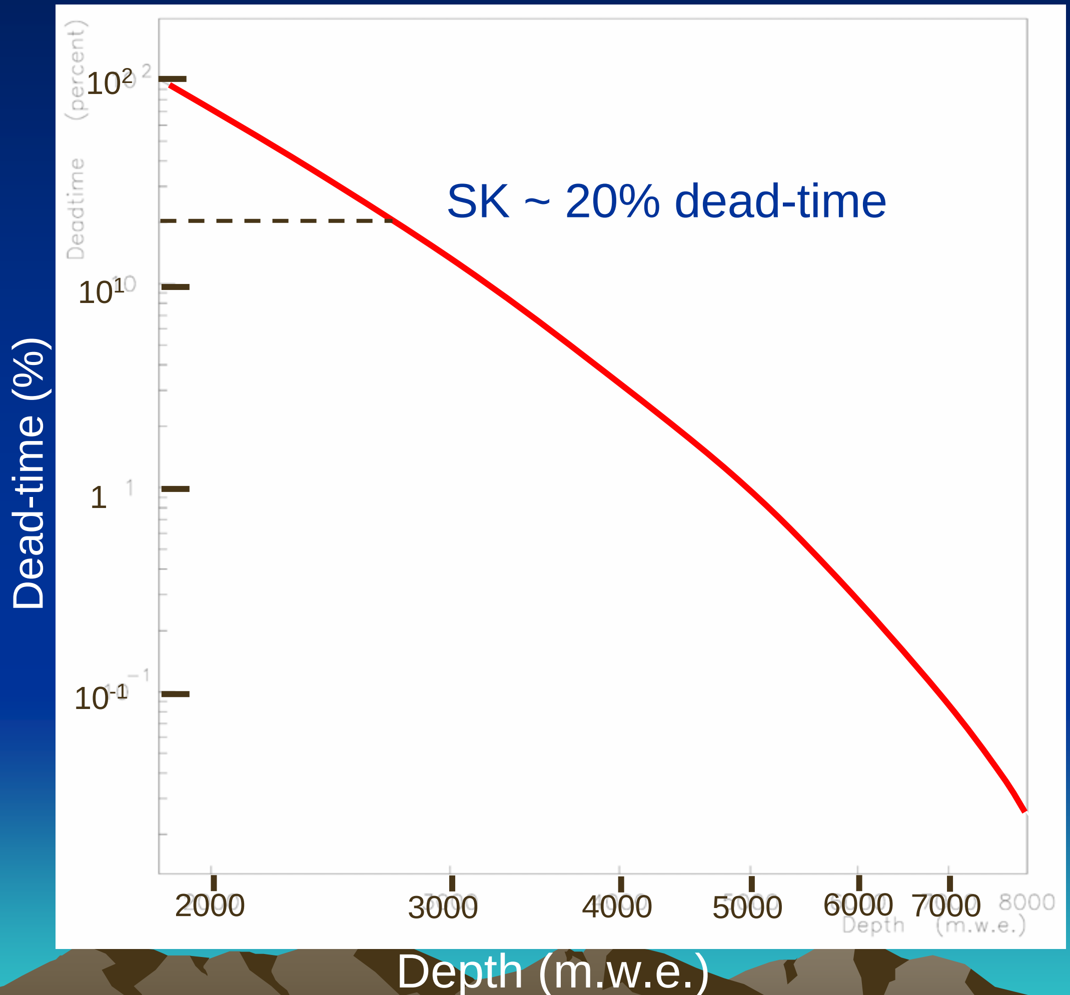
- Possible long baseline target.
- If a supernova occurs at 10kpc, expect ~ 150,000 anti-ν_e events…about a factor of 10 more than all other detectors combined. This varies with detector design.
- Geophysical neutrino measurements can resolve the long-standing issue of the Earth's heat budget
  - requires sensitivity to neutrinos in the range 0.5-2.6 MeV
- Integrated flux from distant SN should produce an isotropic constant flux of ν_e
  - implications for stellar formation rate
  - SK has published limits which are a factor of five above most optimistic models
  - ~200 background events from "stealth" muons and other atmospheric neutrino interactions

Depth Issue



Deep sites => ~ 300 reduction in muon associated background over SK

Spallation Induced Dead-time



0.5 Mton detector at 2700 mwe => 1 spallation event every 6 seconds.

Fast Neutrons

- At mean energies of few 100 GeV, muons produce ~1.5×10^{-4} n/μ/(g/cm^2)
- 6000 n/day at KamLAND
- 60000/day for SK
- ~2×10^5 /day at 2000 mwe
- ~60 /day at 7000 mwe

So, What Depth?

- PDK modes like $e+\pi^0$ and $K^+\nu$ do not require extreme depths.
- Other physics might:
  - Some possible neutron decay modes very difficult to test. e.g., $n\rightarrow 3\nu$

    look for de-excitation of daughter nucleus.

    limit of 4.9×10^{26} years set with Kamiokande.

  Geophysical neutrinos – very low energy.

  Relic SN – stealth muons.

  + …

It seems silly to me to build such a detector and not give it the largest practical shielding.